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AN ANALYSIS OF THE INDICATIONS OF THE UNIVERSITY OF CHICAGO AIRBORNE TURBULENCE INDICATOR IN GUSTY AIR

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WASHINGTON

NACA LANGLEY MEMORIAL AERONAUTICAL LABORATORY

MEMORANDUM REPORT

for the

Air Materiel Command, Army Air Forces

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SUMMARY

From current knowledge there is evidence that the maximum value and the frequency of occurrence of effective gust velocities constitute the most significant characteristics of atmospheric gustiness. On this basis the indications of the University of Chicago airborne turbulence indicator, M-3 modified, obtained during flights in rough air, are discussed as a measure of atmospheric gustiness in relation to simultaneous measurements by the NACA of accelerations experienced by the airplane and of effective gust velocities. The data used for this purpose were obtained from flights of a Beechcraft C-45F airplane through cumulus and alto-cumulus clouds during an investigation of atmospheric turbulence at Chanute Field, Ill.

The results of the analysis reveal that the acceleration indications of the University of Chicago instrument have a definite tendency to be low, with a maximum error of 0.3g for acceleration increments up to about 1.0g. Variations in the airspeed of the airplane may introduce errors of 100 percent or more in the values of effective gust velocity evaluated from the indications of the instrument. The errors limit the usefulness of the instrument for the measurement of maximum effective gust velocity for use in single gust strength design criteria and also for meteorological studies of turbulence. For use in fatigue life studies, there is some possibility of estimating path ratio from the indications of the instrument for determining the total gust frequency.

INTRODUCTION

The problem of reporting atmospheric gustiness from airplanes in flight has been of considerable interest for some time because of its relation to safety of aircraft operations and its applications to meteorology. Experience gained in the past indicates that the problem is twofold, involving first the determination of the characteristics of gustiness which are significant to the structural engineer, meteorologist, dispatcher, and pilot; and second, the development of an instrument to indicate or record those characteristics for use in reporting the gustiness experienced.

Available information relating to the problem of determining the significant characteristics of gustiness indicates that several parameters, some of which are as yet unknown, may be required to specify adequately for all purposes the conditions encountered. For example, reference 1 indicates that the maximum value of the effective gust velocity adequately specifies the single gust strength for airplane wing structures; and, as indicated in reference 2, a knowledge of the frequency of occurrence of all gusts is required for a solution of problems relating to fatigue life of airplane wing structures subjected to the numerous gusts encountered in normal operations. Although much work remains to be done, tests indicate that the effective gust velocity may also be significant in meteorological problems. The results of reference 3, on the other hand, indicate that this quantity is not significant as a measure of the control difficulties experienced by the pilot in rough air, and a criterion of gustiness based on the sequence as well as the intensity of the gusts is cited as a probable requirement. In no case has rationalization been obtained of reports based on the pilot's opinion of the gustiness because of the dependence of such reports on the pilot's experience and the characteristics of the airplane. From information on hand, it therefore appears feasible to consider the maximum effective gust velocity, and the frequency distributions of effective gust velocities, as significant to structural loads and possibly to meteorology, but not to piloting problems.

In an attempt to solve the second part of the problem, the Department of Meteorology, University of Chicago, has recently developed an instrument to provide information on the intensity of atmospheric gustiness encountered in flight. The NACA was requested on May 28, 1945, to test this instrument. A joint investigation of atmospheric turbulence conducted by the U. S. Army Weather Services, the University of Chicago, and the NACA at Chanute Field, Ill., offered an opportunity to fulfill this request in addition to providing data of general usefulness on atmospheric gustiness. The present report has been prepared to discuss the indications obtained from the University of Chicago turbulence indicator in relation to simultaneous measurement of atmospheric gustiness made by the NACA, which are summarized herein.

The discussion will be limited to the intensity and frequency of occurrence of the effective gust velocity since these characteristics of gustiness are known to be significant in relation to certain problems arising from flight in rough air.

APPARATUS AND INSTRUMENTS

The University of Chicago airborne turbulence indicator, Model M-3 modified, is essentially a modified accelerometer. The accelerometer element consists of a spring-supported mass having a natural frequency of about 4 cycles per second. Although no damping was intentionally introduced, a small but unknown amount of frictional damping is present in the system. The deflection of the mass varies the position of a sliding contact on a center-tapped resistance producing a unidirectional voltage output which is proportional to impressed positive and negative normal acceleration increments. The unidirectional voltage is applied to a standard Esterline-Angus recording milliammeter through an electronic circuit. The current response of the electronic circuit is directly proportional to voltage pulses from the accelerometer element up to their maximum values, but decays from the maximum values at a relatively slow linear rate, equivalent to 0.95g per minute. The introduction of the slow decay results in two effects: first, a series of small accelerations produce a sustained unidirectional indication which appears as an apparent zero shift; secondly, the slow decay from large acceleration peaks conceals all succeeding acceleration increments which are smaller than the instantaneous magnitude of the decay ordinate.

For the subject tests, the University of Chicago instrument was mounted at the center of gravity of the test airplane, oriented to react to normal accelerations. The recorder which was set to give a paper speed of 12 inches per hour was in continuous operation throughout each flight. The records were synchronized with records of other instruments by means of a marker pen which operated whenever the other instruments were turned on or off.

Measurements of atmospheric gusts in flight were made with the following instruments installed near the airplane center of gravity:

1. NACA air-damped recording accelerometer
2. NACA airspeed-altitude recorder
3. NACA synchronous timer

Because of a limited record capacity these instruments were operated in rough air only.

The characteristics of the NACA accelerometer were selected on a basis of a vane frequency three times the frequency of the impressed normal accelerations and 0.7 critically damped. The frequency of impressed accelerations was estimated from gust data presented in references 4 and 5. These references indicate that the shortest and the most probable gust gradient distances are about 2 and 10 chord lengths, respectively. Considering the impressed frequency as corresponding to a period of four times the time from zero to peak acceleration, for a normal flight speed of 165 miles per hour the impressed frequencies are computed to be 3.75 to 0.75 cycles per second, respectively. The accelerometer accordingly was provided with a vane frequency of 11.4 cycles per second and was approximately 0.7 critically damped.

The airspeed-altitude recorder was connected to the pitot-static leads of a special airspeed head attached to, but extending about 8 inches lower than, the service airspeed head beneath the nose of the airplane. Both the airspeed-altitude and acceleration recorders were set to give a record speed of 1/8 inch per second and were synchronized by means of the 1-second-interval timer.

The instruments described were installed in a Beechcraft Model C-45-F airplane supplied by the Army Air Forces. Pertinent dimensions of this airplane as flown are given in the following table:

Gross weight at take-off, pounds	8000
Wing area, square feet	349
Wing loading at take-off, pounds per square foot	22.9
Span, feet	47.8
Length, feet	34.2
Mean aerodynamic chord, feet	8.06
Center-of-gravity location, percent mean aerodynamic chord	21.4
Slope of lift curve, per radian	4.5

TESTS AND RESULTS

The tests consisted of a series of horizontal flight traverses through rough air with the airplane trimmed for steady level flight, while recording gustiness on the University of Chicago instrument and airspeed and normal acceleration on the NACA instruments. Most of the flight operations were in cumulus and alto-cumulus clouds at speeds from 150 to 165 miles per hour. Since only few acceleration increments greater than 0.5g were experienced at these speeds because of the light intensity of the gustiness, clouds were intentionally traversed in some instances at speeds up to 215 miles per hour in order to increase the accelerations.

The records of acceleration and airspeed obtained from the NACA instruments were evaluated to obtain the effective gust velocities U_e by use of the formula (reference 6):

$$U_e = \frac{2\Delta nW}{\rho_o aV\sigma^{1/2}SK}$$

in which

U_e effective gust velocity, feet per second

Δn normal acceleration increment, g

W gross weight of the airplane, pounds

ρ_o air density at sea level, slugs per cubic foot

$V\sigma^{1/2}$ equivalent airspeed of airplane, feet per second

a slope of lift curve, per radian

K relative alleviation factor taken from figure 1 of reference 6 (K = 1.06 for wing loading of 22.9 pounds per square foot)

The effective gust velocities are summarized together with the maximum acceleration increment and the average indicated airspeed for each traverse in table I. No attempt was made to refine the gust velocity calculations by taking into account airplane stability as such refinement normally requires tests of a model of the airplane in the NACA gust tunnel and is appreciable only for unconventional airplanes or for the larger gusts (gradient distances of about 20 chords or more).

The records obtained from the University of Chicago turbulence indicator were evaluated by use of a static calibration supplied with the instrument to obtain the maximum acceleration increment for each cloud traverse. Examination of the records, however, left some doubt as to the proper datum line from which the records should be read inasmuch as a zero shift, as indicated in figure 1 by the varying record line for level flight in smooth air, may have occurred during any flight. Three methods of reading the records were therefore used:

Method I - the zero ordinate of the record chart was used as a datum line

Method II - the average indication of the instrument for all periods of time in smooth air for each flight was used as a datum line

Method III - the indication of the instrument in smooth air immediately preceding and following each traverse was used as a datum line

Method I was judged to be the normal and most logical method of record reading. Due to the apparent zero shift, however, the other methods were considered. The results obtained by utilizing Method I are summarized in table I and are shown plotted against the corresponding maximum acceleration increments evaluated form the NACA accelerometer records in figure 2. For purposes of comparison, the mean lines of the data obtained when using Methods I, II, and III of reading the University of Chicago records are shown in figure 3.

PRECISION

The dynamic characteristics of the University of Chicago turbulence indicator were not available to the NACA for estimation of instrument errors under various flight conditions. Based on the static calibration supplied, however, the records were read to within $\pm 0.01g$.

The accuracy of the NACA acceleration measurement was determined by dropping the accelerometer on calibrated springs to obtain one-half sine waves of impressed accelerations with equivalent frequencies up to 5 cycles per second. These tests indicated that the dynamic errors were less than 0.05g. It is felt, therefore, that the flight records of acceleration were also accurate to within that limit. The NACA accelerometer records were also read to within ±0.01g.

As the airspeed installation was not calibrated and no correction was made for compressibility effect, the term $V\sigma^{1/2}$ given in the effective gust velocity formula in reference 6 as used is actually V_i uncorrected indicated airspeed. Experience with similar airspeed installations indicated errors not greater than ±3 feet per second for the speed range of the airplane.

Although the gross weight of the airplane at take-off was used in computing the effective gust velocities during the ensuing flight, the change in weight due to fuel consumption was found to introduce negligible error in the data.

The maximum error in the effective gust velocity resulting from errors in the airspeed-acceleration measurements is ±2 feet per second.

DISCUSSION

In view of the fact that the University of Chicago turbulence indicator is designed to measure acceleration and not gust velocity, the indications of the instrument are dependent to a large degree upon flight speed and airplane characteristics. The data have consequently been considered to determine, first, the accuracy of the acceleration indications; and second, the usefulness of the indications in defining characteristics of gustiness.

Figure 2 indicates that there is a strong tendency for the University of Chicago turbulence indicator to read low as compared to the NACA accelerometer and that the maximum difference in the readings is 0.3g for acceleration increments up to 1.0g. These results together with the scatter of the points probably are due to a number of causes including the low frequency of the University of Chicago accelerometer unit, the response of the electronic circuit to acceleration pulses of various shapes, and to the slow response of the Esterline-Angus recorder.

Figure 3 indicates that least error in reading the University of Chicago instrument records is introduced by Method I although the slope of the line corresponding to Method II is closer to 45°. The zero off-set, methods II and III, probably results from the voltage output corresponding to the deflection of the accelerometer vane under engine vibrations.

Application of the University of Chicago turbulence indicator as an indicator of maximum effective gust velocity is seriously handicapped since the errors arising from scatter of the data together with the tendency of the instrument to indicate unconservative gust load factors are further augmented by errors arising from the use of an accelerometer alone as an indicator of effective gust velocities. The additional error results from variations of the airspeed at which the airplane is operated. Errors arising from the various operating speeds shown in Table I become apparent as an increase in the scatter of the data as shown in figure 4 where the maximum acceleration increment for each traverse as recorded by the University of Chicago instrument is plotted against the corresponding maximum effective gust velocity as computed from instantaneous values of acceleration and airspeed from the NACA instruments. Figure 4 shows that over-all errors of 100 percent or more may be introduced in the indications of maximum effective gust velocities.

Errors of this magnitude seriously handicap the application of the instrument to the measurement of maximum effective gust velocity as a single gust-strength criteria for structural design of airplane wings or to its use in connection with meteorological studies, although for the latter errors up to 20 percent do not appear too serious.

Since it does not respond to acceleration increments that are smaller than the instantaneous magnitude of the decay ordinate from a preceding large acceleration peak, the University of Chicago instrument gives no direct information on the frequency of occurrence of gusts such as would be desired for studies of the fatigue life of airplane wings. However, there is some possibility that the path ratio as used in reference 6 may be estimated from the records, and equation (2) of reference 6 may then be used to estimate the total gust frequency. The path ratio may be found from the length of flight in rough air having effective gust velocities greater than 0.3 foot per second and the total length of flight. Since this gust velocity corresponds to an acceleration increment of only about 0.02g for conventional airplanes at an indicated speed of 165 miles per hour, such small variations are likely to be difficult if not impossible to observe from the records of the University of Chicago instrument.

CONCLUDING REMARKS

From an analysis of the records of the University of Chicago turbulence indicator taken in rough air in relation to simultaneous measurements of acceleration and effective gust velocities by the NACA, the following conclusions have been drawn:

1. The acceleration indications of the University of Chicago turbulence indicator have a definite tendency to be low with a maximum error of 0.3g for acceleration increments up to about 1.0g.

2. Additional errors inherent in the use of an accelerometer as an indicator of maximum effective gust velocity, due to variations in operating airspeed may result in an over-all error of 100 percent or more in the values of effective gust velocity evaluated from the indications of the University of Chicago instrument. These errors limit the usefulness of the instrument for evaluating the maximum effective gust velocity for use in single gust-strength design criteria and also for meteorological studies of turbulence.

3. Although there is no direct method of determining the frequency of occurrence of gusts from the records of the University of Chicago instrument, there is some possibility of estimating path ratio for determining the total gust frequency for use in fatigue life studies.

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TABLE I

SUMMARY OF ACCELERATION AND GUST VELOCITY MEASUREMENTS
WITH C-45-F AIRPLANE

Flight number	Run	Average indicated airspeed (mph)	Δn_{max} (g)		Effective gust velocity, U_e (fps)										
					0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22
			[a]U of C	NACA	Frequency										
1	14	150	0.06	0.12	---	7	---	---	-----	-----	-----	-----	-----	-----	-----
	30	160	.39	.42	2	10	5	2	1	-----	-----	-----	-----	-----	-----
2	1	126	.30	.45	---	13	36	2	4	1	-----	-----	-----	-----	-----
	2	130	.27	.34	---	12	12	1	2	-----	-----	-----	-----	-----	-----
	3	130	.26	.39	---	3	4	---	1	-----	-----	-----	-----	-----	-----
	13	184	.44	.53	1	26	6	4	1	-----	-----	-----	-----	-----	-----
	14	181	.26	.33	2	7	4	---	-----	-----	-----	-----	-----	-----	-----
	15	167	.30	.42	1	18	4	4	-----	-----	-----	-----	-----	-----	-----
	16	147	.23	.35	5	1	1	1	-----	-----	-----	-----	-----	-----	-----
	17	126	.16	.19	---	4	1	---	-----	-----	-----	-----	-----	-----	-----
	18	126	.16	.19	---	1	2	---	-----	-----	-----	-----	-----	-----	-----
3	14	171	.28	.35	28	99	8	1	-----	-----	-----	-----	-----	-----	-----
	15	164	.19	.22	9	33	---	---	-----	-----	-----	-----	-----	-----	-----
4	13	201	.39	.44	1	7	5	1	-----	-----	-----	-----	-----	-----	-----
	15	198	.64	.50	5	36	18	1	-----	-----	-----	-----	-----	-----	-----
5	1	130	.26	.23	---	10	8	---	-----	-----	-----	-----	-----	-----	-----
	2	126	.19	.30	---	3	11	2	-----	-----	-----	-----	-----	-----	-----
	3	130	.29	.35	---	5	5	2	2	-----	-----	-----	-----	-----	-----
	4	126	.22	.30	---	10	5	2	-----	-----	-----	-----	-----	-----	-----
	5	126	.13	.22	---	5	3	1	-----	-----	-----	-----	-----	-----	-----
	15	215	.67	.55	2	1	2	3	-----	-----	-----	-----	-----	-----	-----
	16	177	.41	.51	4	86	21	16	3	-----	-----	-----	-----	-----	-----
	17	188	.26	.48	---	13	3	3	-----	-----	-----	-----	-----	-----	-----
	18	181	.31	.31	1	17	3	---	-----	-----	-----	-----	-----	-----	-----

[a]Evaluated according to method I

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COMMITTEE FOR AERONAUTICS

TABLE I - Concluded.

SUMMARY OF ACCELERATION AND GUST VELOCITY MEASUREMENTS
WITH C-45-F AIRPLANE - Concluded

Flight number	Run	Average indicated airspeed (mph)	Δn_{max} (g)		Effective gust velocity, U_e (fps)										
					0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22
			[a]U of C	NACA	Frequency										
5	19	184	0.29	0.48	---	18	7	2	----	-----	-----	-----	-----	-----	-----
6	1	133	.16	.19	---	4	1	---	----	-----	-----	-----	-----	-----	-----
	2	126	.13	.17	---	4	1	---	----	-----	-----	-----	-----	-----	-----
	5	130	.19	.35	---	7	7	2	----	-----	-----	-----	-----	-----	-----
	14	208	.54	.85	3	29	19	2	1	1	-----	-----	-----	-----	-----
	15	198	b	.22	1	4	---	---	----	-----	-----	-----	-----	-----	-----
7	15	174	.33	.41	7	45	7	4	----	-----	-----	-----	-----	-----	-----
8	15	181	c	1.34	---	23	5	12	9	2	2	1	-----	-----	1
	16	164	c	1.12	2	26	21	26	9	5	2	-----	1	1	-----
	17	177	c	.84	---	8	12	4	2	-----	1	-----	-----	-----	-----
	18	164	c	.94	1	3	8	8	3	2	2	1	1	-----	-----
	19	174	c	.54	---	15	12	5	----	-----	-----	-----	-----	-----	-----
	20	164	c	.48	2	29	14	4	----	-----	-----	-----	-----	-----	-----
	21	164	c	.86	2	52	39	19	5	1	2	-----	-----	-----	-----
9	6	126	.37	.45	---	13	24	3	3	-----	-----	-----	-----	-----	-----
	7	123	.39	.42	---	6	17	6	5	-----	-----	-----	-----	-----	-----
	8	126	.74	.92	---	2	10	---	6	-----	-----	1	-----	1	-----
	12	177	.62	.70	---	3	4	9	2	1	-----	-----	-----	-----	-----
	13	181	.95	1.05	---	30	14	15	2	-----	2	-----	-----	1	-----
	14	177	.52	.60	1	30	13	7	----	1	-----	-----	-----	-----	-----
11	14	136	.29	.19	---	6	10	---	----	-----	-----	-----	-----	-----	-----
	18	130	.23	.17	---	8	1	---	----	-----	-----	-----	-----	-----	-----
	24	109	.17	.15	---	---	4	---	----	-----	-----	-----	-----	-----	-----

[a]Evaluated according to method I. [b]Record obliterated. [c]Instrument not operating properly.

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L-723

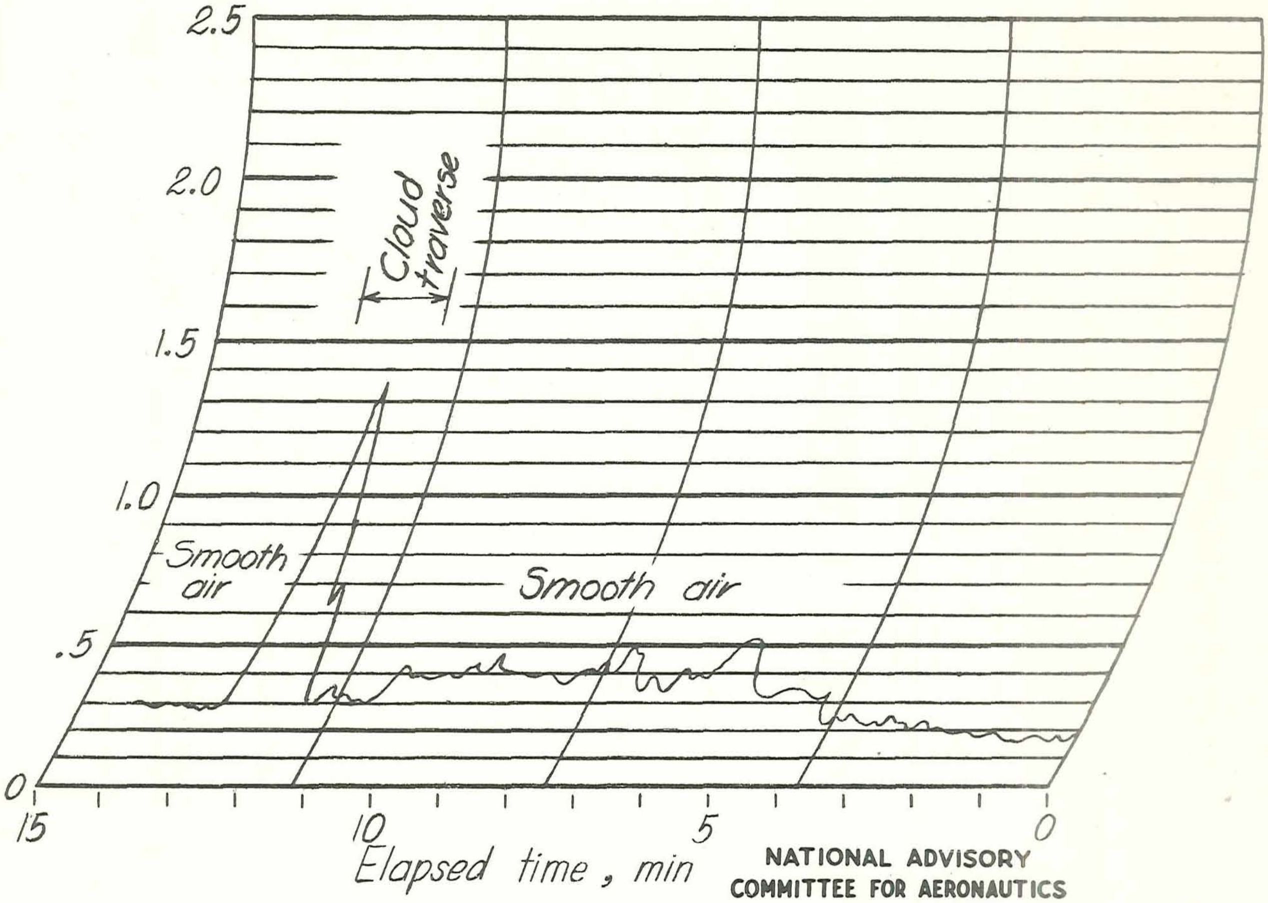

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Figure 1. - Sample record obtained from University of Chicago turbulence indicator for flight proceeding, during, and following a traverse through alto-cumulus cloud.

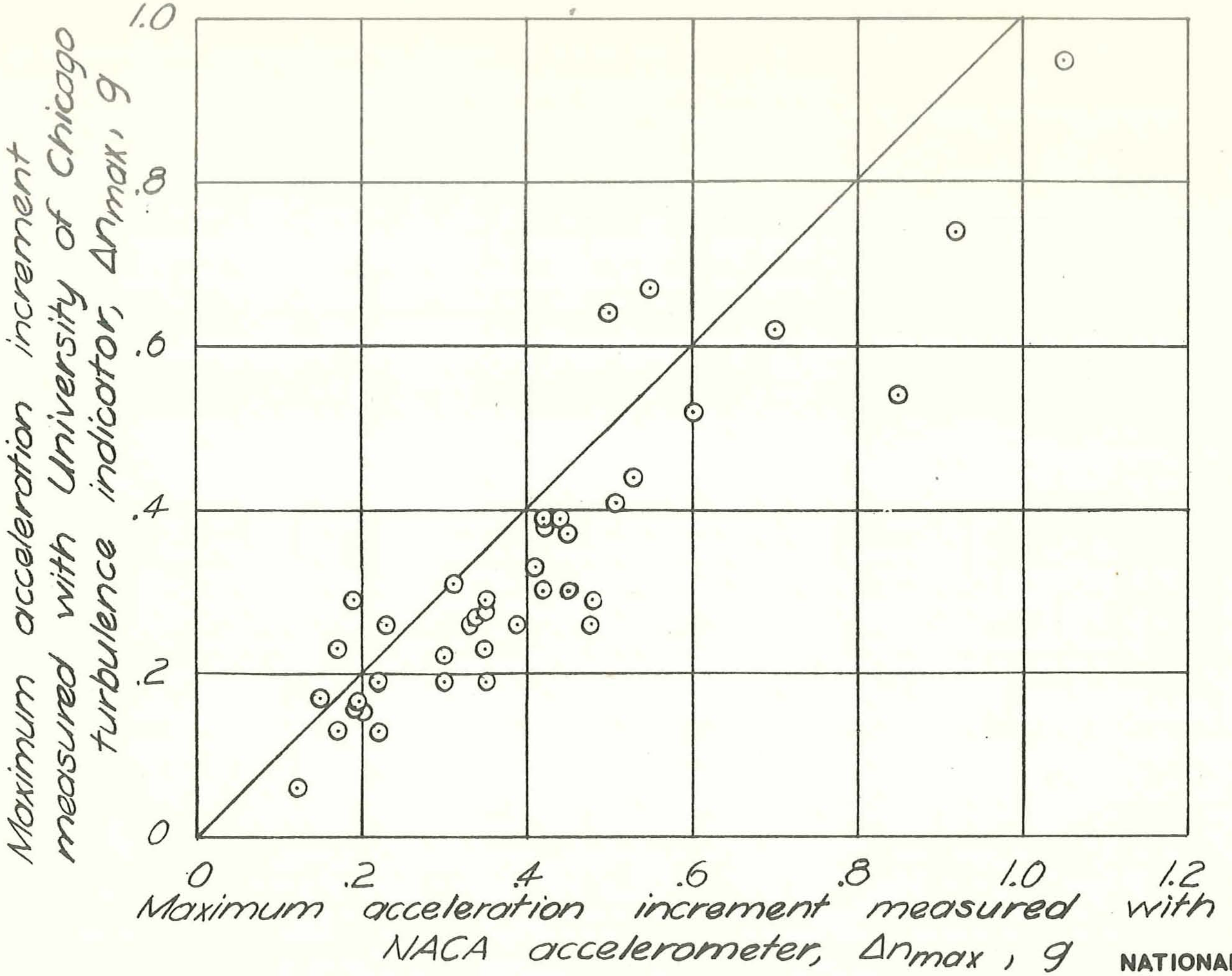

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Figure 2.- Comparison of maximum acceleration increments measured with University of Chicago turbulence indicator (Method I) and NACA accelerometer during separate cloud traverses.

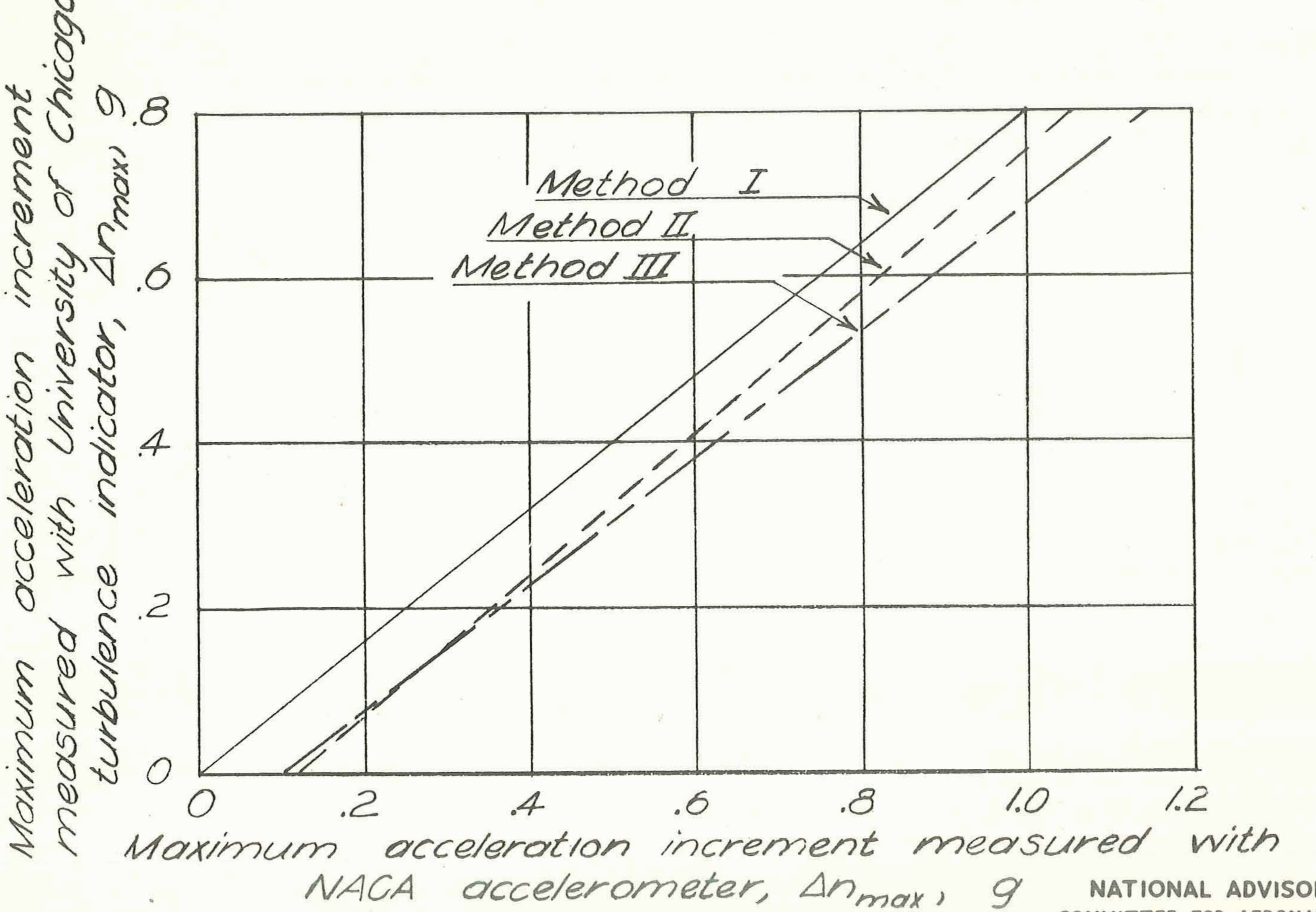

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Figure 3.- Variations in the trends of maximum acceleration data using three methods of reading University of Chicago turbulence indicator records.

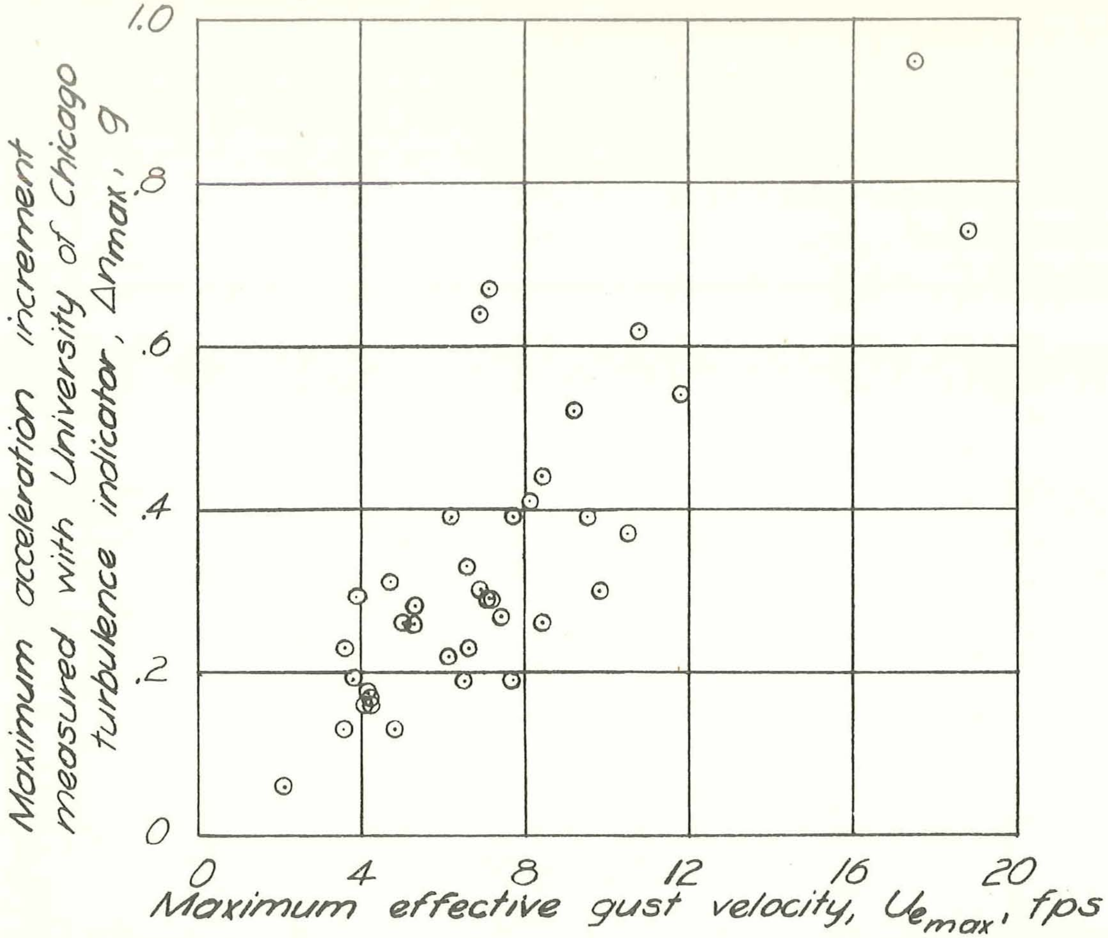

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Figure 4.- Comparison of maximum acceleration increments measured with University of Chicago turbulence indicator (Method I) with maximum effective gust velocities for separate cloud traverses.